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Effects of land use and climate change on erosion intensity and sediment geochemistry at Lake Lehmilampi, Finland

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Abstract

This paper aims to evaluate the possible relationships between erosion intensity and changes in climate and land use during the past 5.5 cal. k years at Lake Lehmilampi, eastern Finland. In this study we compare a detailed geochemical sediment record with (1) forest and land use history inferred from the first pollen and charcoal records from Lake Lehmilampi, and (2) existing archaeological surveys and independent proxy-records of climate change in the study region. The physical and geochemical sediment parameters examined include grain size analysis data and 23 chemical elements, determined with four selective extractions and ICP-MS. There are indications of possible human impact in the lake catchment as early as the Neolithic period, c. 3000–2550 BC, but the first undisputable signs are dated to 1800–100 BC. Cereal pollen reappears at c. AD 1700 and increases rapidly until c. AD 1950. The Holocene Thermal Maximum, its end c. 2000 BC, and the 'Medieval Climate Anomaly' were major climate events that had a prominent effect on erosion intensity, while human impact was a more significant factor during the period 3000 BC–AD 800 and from AD 1500 onwards. Although signs of changes in erosion intensity found in the sediment were small in this small catchment, they were significant enough to have a clear impact on the fraction of potentially mobile element species. This fraction increases with decreasing erosion intensity, which is probably related to a higher degree of chemical weathering and leaching during periods of decreased erosion.

Keywords

climate change, erosion, geochemistry, human disturbances, land use, varved sediment, weathering

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Introduction

Varved lake sediments may provide very detailed records of past environmental conditions, both in the lake itself and in its catchment area, providing key information about how the environment responds to natural or human disturbances. Among possible responses, alterations in the flow of elements in the environment, including erosion of surface soils, may be of interest. Erosion, here defined as the physical removal of topsoil particles with surface water runoff, may be affected by climate through changes in water runoff intensity following, for example, altered precipitation patterns. Erosion may also be affected by forest fires (natural or human-induced), and by other human activities such as deforestation, cultivation or grazing (e.g. Dotterweich, 2008; Enters et al., 2008; Ojala and Alenius, 2005; Tiljander et al., 2003; Zolitschka, 2003).

Element concentrations and sediment accumulation rates in Lake Lehmilampi (eastern Finland) during the mid and late Holocene have been described by Augustsson et al. (2010). The aims of this follow-up paper are to:

(1) Evaluate the possible relationship between erosion intensity and changes in climate and land use during the mid and late Holocene.
(2) Address the effect of erosion intensity on the fraction of potentially mobile element species in the eroded material, inferred from four selective extractions and ICP-MS analysis.

In order to achieve the first objective, we conducted the very first pollen and charcoal analyses at Lake Lehmilampi with the purpose of reconstructing the vegetation and land use history around the site. Moreover, we consulted the existing archaeological record in the study area in order to compare it with the interpretation of the pollen and charcoal records, and we evaluated our multiproxy records in light of published, independent proxy data of regional climate change. A conceptual model of the processes discussed in this study is shown in Figure 1.

The study site

Lake Lehmilampi is a small lake in northern Karelia, eastern Finland (63°63′N, 29°10′E) (Figure 2a). It is located in the boreal zone, where many lakes are found to have been sensitive to climate change (Hammarlund et al., 2003; Heikkilä and Seppä,

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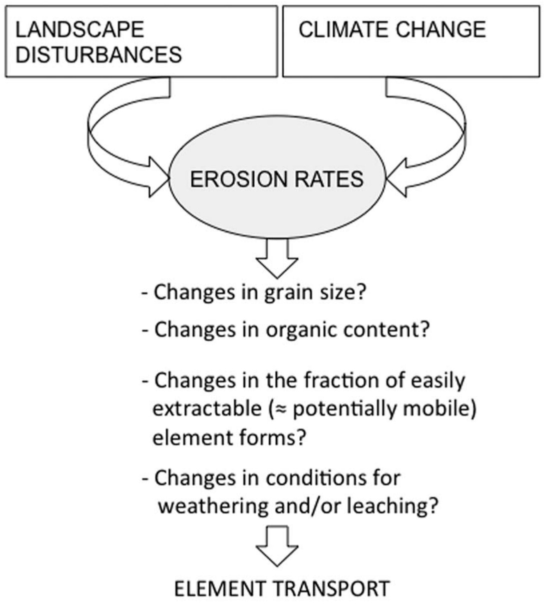


Figure 1. Schematic overview of the problem addressed in the paper, see text for explanation.

2003; Itkonen and Salonen, 1994; Seppä et al., 2005). The lake size and catchment are c. 0.15 km^2 and 1.5 km^2, respectively. Two 11 m deep basins are located in the southern part of the lake. The dominant tree species in the catchment area are pine and spruce, and the bedrock, consisting of acidic Archaean rocks, is often exposed (Luukkonen, 2003). The soil overburden is composed of thin Quaternary tills and fine-grained sediments may occur in depressions, originating from the time when Lake Lehmilampi was part of Lake Pielinen, one of the largest lakes in Finland, from which it was isolated c. 3100 BC (Haltia-Hovi et al., 2010). The present mean annual temperature is 2°C, with mean summer (July) temperatures of 16°C, and mean winter (January) temperatures of −10°C. Half of the annual precipitation (700–750 mm) is deposited as snow. The lake is usually frozen from mid November to mid May, when the spring meltwater discharge accounts for about half of the annual runoff. The lake is surrounded by hills, and the catchment borders are located about 55 m above the lake water surface. Lake catchments in hilly landscapes tend to be particularly prone to physical erosion. This is obviously the case in Lake Lehmilampi's catchment as the dominant part of the lake sediment is composed of allochthonous mineral matter that has been washed into the lake mainly during snowmelt (Haltia-Hovi et al., 2007). The sediment is varved, starting from the time of the isolation of the lake. There is a continuous increase in varve thickness in the upper 6 cm of the sediment sequence, but no systematic relationship between depth and varve thickness in the remaining part of the core could be found, which implies that compaction effects are only crucial for the interpretation of the uppermost centimetres of the sediment.

Materials and methods

Three overlapping subcores were used to extract a 486 cm long sediment sequence for geochemical analyses. The geochemical characteristics and trends of the entire sediment sequence, hereafter referred to as the 'geochemical core', have been described and discussed by Augustsson et al. (2010). It was only possible to visually identify individual varves in a few segments of the core. These distinct marker zones enabled the matching of overlapping subcores, but subsampling for geochemical analyses had to be made in continuous 1 cm segments rather than defined time intervals. The analyses presented in this paper were conducted on sediment from the same subsamples and we adopted the chronology that was established earlier in Augustsson et al. (2010), where the geochemical core was matched against a previously dated core .

Erosion intensity

Variations in the erosion intensity can be inferred either from the estimates of total mineral matter accumulation available from the x-ray density analyses of the dated core (Haltia-Hovi et al., 2010), or from the variations in ash content measured in the geochemical core. These two variables showed strong positive correlation in the Lake Lehmilampi sediment (n=76; r=0.78; p<0.05; Augustsson et al., 2010). In order to study the possible relationships between changes in erosion from the catchment and vegetation/land use changes, it was essential to compare data of exactly the same age. We chose to use the ash content from the geochemical core as an indicator of relative changes in erosion intensity since it could be directly correlated with the results of the chemical leaches and the pollen and charcoal records from the same core. We define high, respectively low erosion intensity as ash content values above the third quartile (> 87.9%; n= 486; Augustsson et al., 2010) and below the first quartile (< 84.2%).

Pollen and microcharcoal analysis

To establish whether major shifts in erosion intensity were related to changes in vegetation and/or land use, 32 subsamples from the geochemical core were selected for pollen and microcharcoal analysis around major shifts in the ash content.

Eight tablets of *Lycopodium clavatum* spores were added to 1 g of dry sediment for calculation of pollen concentrations (PCs, pollen grains/g per yr) and pollen accumulation rates (PARs, pollen grains/cm^2 per yr) (Stockmarr, 1971). Sample treatment followed the acetolysis method (Berglund and Ralska-Jasiewiczowa, 1986), and a minimum of 500 pollen grains per sample were identified using keys (Beug, 2004; Punt et al., 1976–2003) and the reference collection at the Laboratory of Palaeoecology at Linnaeus University.

Microcharcoal fragments >10–25 µm and >25–250 µm were counted on the pollen slides following the method used by e.g. Berglund et al. (1991) and Greisman and Gaillard (2008). The sediment from the studied subsamples did not contain any plant macroremains or macrocharcoal fragments >250 µm.

Pollen diagrams, including the microcharcoal records, were drawn using the TILIA and TILIAGRAPH programs (Grimm, 1990). The pollen sum (S) used for calculation of percentages includes all pollen of terrestrial plants (Berglund and Ralska-Jasiewiczowa, 1986). Percentages of charcoal fragments and taxa excluded from the pollen sum were calculated using the pollen sum S with the addition of the count for the excluded taxon/charcoal particle-fraction. Pollen assemblage zones were identified by constrained cluster analysis (Coniss; Grimm, 1987) as implemented in TILIAGRAPH. PCs were calculated in TILIA, and PARs by multiplying PCs with the weight of the 1 cm thick original sample (g), and dividing the result with the number of years represented in the sample and the area of the core section (cm^2). Palynological richness (estimated number of pollen taxa $E(Tn)$)

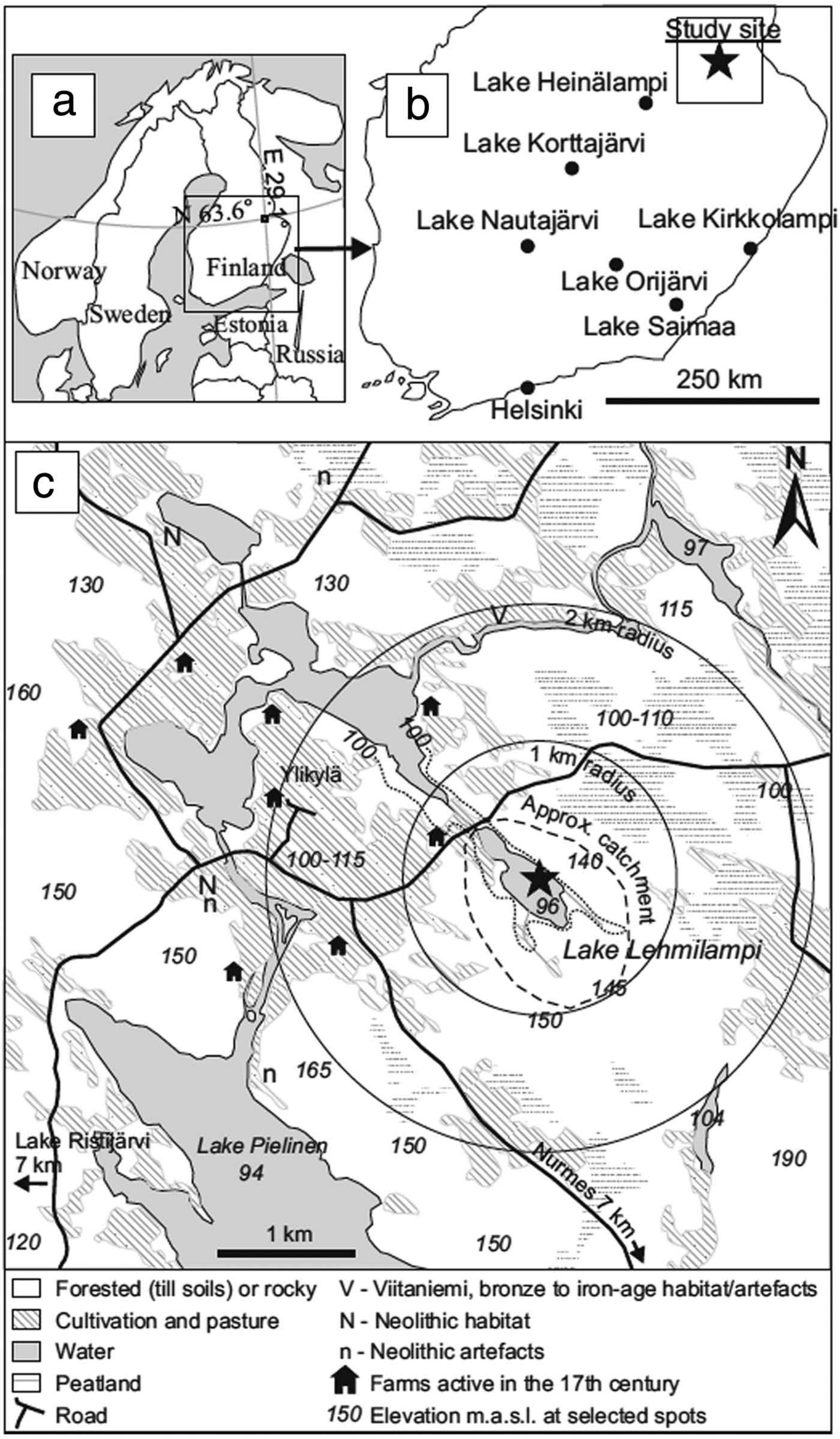


Figure 2. Location of Lake Lehmilampi north of Lake Pielinen in eastern Finland. The dashed line shows the lake catchment as estimated from topographical maps.

was estimated using the rarefaction analysis of Birks and Line (1992). All terrestrial spermatophytes and pteridophytes were included in the analysis.

Grain size analysis

Size fractionation was determined with a Micromeritics SediGraph 5120 at the Department of Geology at Lund University, Sweden. The SediGraph analysis is based on continuous x-ray scanning of particle settling through a liquid medium of known density and viscosity by applying Stokes law. The principles of the method, reproducibility, and confidence limits are described by Jones et al. (1988). The grain size analysis was conducted on 91 samples from the geochemical core. Prior to analysis, samples were treated with 30% hydrogen peroxide and 10% hydrochloric acid to remove organic matter and carbonates respectively. For dispersion of the particles, samples were suspended in 100 ml 0.5% sodium pyrophosphate and shaken overnight. The suspension was filtered through a 63 μm sieve and centrifuged to 50 ml. Before analysis, samples were treated for 30 s with an ultrasonic probe. Measurements were made in intervals down to the 0.5 μm level. In this paper, however, only the clay size fraction (<2 μm) is reported in order to examine whether an increase in small particles occurred during periods of high or low erosion intensity, as fine-grained material should contain a higher proportion of easily weathered element forms than coarse material.

Geochemical analyses

Material from the same 22 subsamples used for pollen and charcoal analysis was treated for sequential extractions. Three fractions were targeted using the sequential extraction procedure suggested by Hall et al. (1996) and Hall (1998). The first extraction targets elements in exchangeable forms and bound to carbonates (*Exch*) by the addition of 1.0 M sodium acetate. The second extraction releases organically bound elements using 0.1 M pyrophosphate (*Org*), and the third one releases elements associated with amorphous Fe and Mn oxyhydroxides by adding 0.25 M hydroxylamine (*Fe/Mn*). Total element concentrations were determined after digestion with a mixture of hydrofluoric acid, hydrochloric acid, perchloric acid and nitric acid (*Tot*). The total extraction was conducted with fresh material instead of analyzing the residual fraction as a final step in the sequence.

The following elements were determined with ICP-AES/MS at Actlabs, Canada: Al, As, Ba, Ca, Ce, Co, Cu, Fe, Ga, K, La, Mg, Mn, Ni, Pb, Rb, S, Sr, Th, U, V, Y, Zn. Concentrations in each fraction were recalculated into annual accumulation rates, in a similar way as described for pollen concentrations above. The total *potentially mobile fraction* (PMF) of elements (%) was calculated from the annual accumulation rates (mg/m^2 per yr) of the different fractions according to:

$$\mathrm{PMF} = [(Exch + Org + Fe/Mn) / Tot) \times 100 \qquad (1)$$

Results and discussion

Land use and fire history

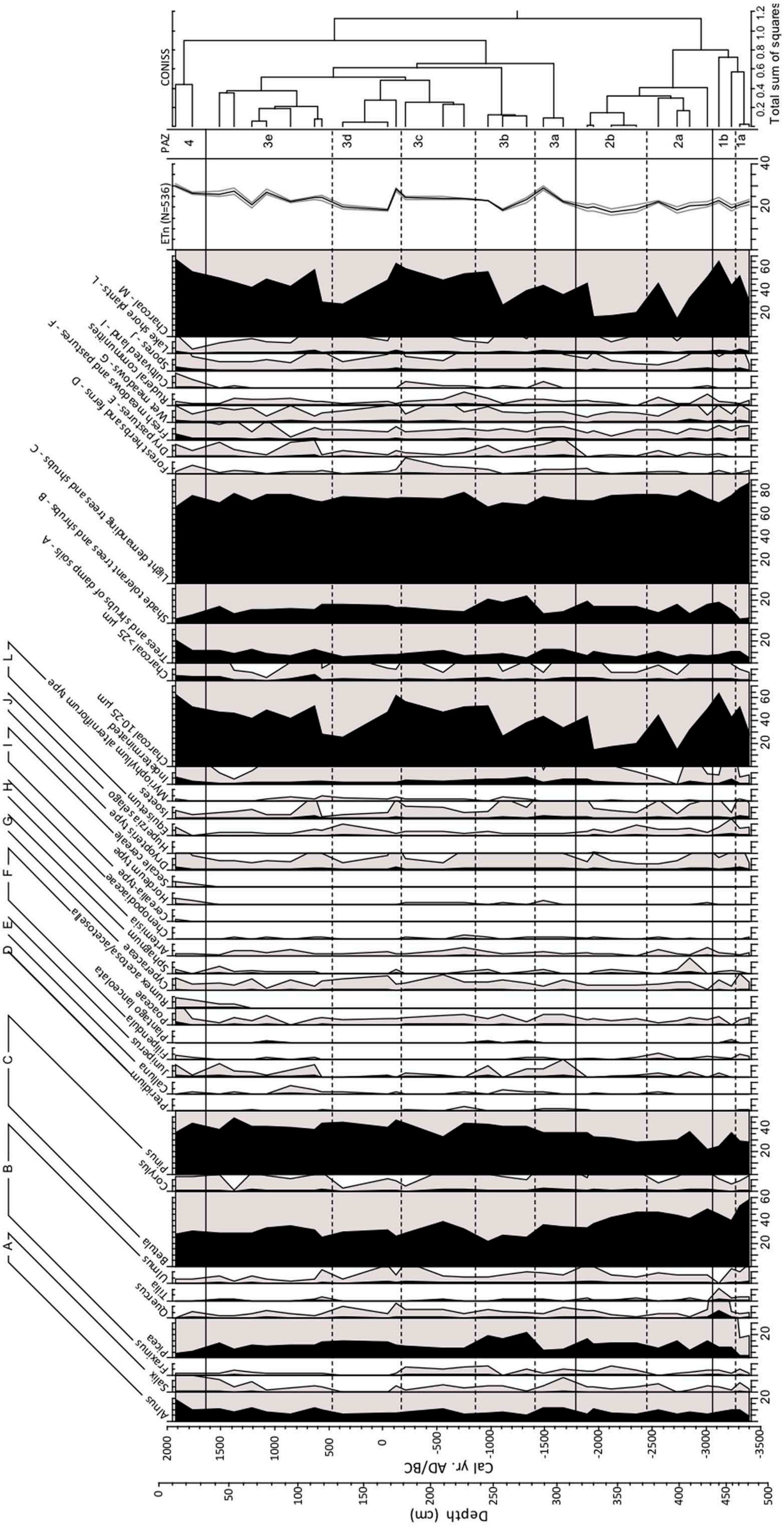
As one of the study's aims is to compare inferred erosion intensity from the lake catchment with changes in climate, vegetation and land use, it is necessary to define the size of the area around the lake for which the pollen and charcoal records are representative. To date, a concept of the source area exists for pollen assemblages in lake sediments, i.e. the relevant source area of pollen (RSAP) sensu Sugita (1994). The RSAP of small sites can be estimated when there are a number of pollen records from small and large lakes available in the study region, which is not the case here. The radius of the RSAP for small lakes in forested to half open landscapes was estimated to range between 800 m and 2000 m in southern Sweden (Hellman et al., 2009a, 2009b; Sugita et al., 1999). Here we assume that the RSAP of Lehmilampi is/was of similar size and, therefore, comparable with the size of the watershed catchment area of the lake (c. 1.5 km^2). Below, 'study area' refers to the lake catchment area and the RSAP, while 'study region' refers to a larger area around the lake of 2.5^3–10^3 km^2.

The definition of the RSAP also implies that it is the smallest area for which a pollen-inferred quantitative reconstruction of vegetation abundance (in percentage cover within the lake's RSAP) can be achieved using the Landscape Reconstruction Algorithm (LRA) of Sugita (2007). The LRA also requires that a number of pollen records from small and large lakes are available in the study region. In this study we thus need to use general insights from quantitative reconstructions in other regions when we interpret the pollen record from Lake Lehmilampi. Although pollen assemblages from small lakes primarily include pollen grains from the local vegetation within the lake's RSAP, a significant fraction of the pollen assemblage (the 'background pollen' sensu Sugita, 2007) originates from the regional vegetation. The background pollen fraction is particularly large when the regional vegetation is characterised by high pollen producers such as *Betula* and *Pinus* (e.g. Broström et al., 1998), which is the case in our study region. In such circumstances, non-arboreal pollen (NAP) strongly underestimates the cover of local herbaceous plants (Hellman et al., 2009b; Sugita et al., 1999). Therefore, we assume that the pollen record from Lehmilampi can be interpreted in terms of local vegetation changes, i.e. within the watershed catchment of the lake or slightly larger (a 2 km radius area around the lake), and that the percentages of NAP in the pollen record at Lehmilampi are an underestimation of the actual cover of open vegetation within the RSAP of the lake.

The source area of microscopic and macroscopic charcoal fragments has been discussed by many authors, but a consensus has so far not been reached (see Greisman and Gaillard, 2008, for a detailed discussion). Here we assume that the size fractions 10–≤ 25 μm and >25–250 μm roughly represent regional respectively local fire activity. In a study of Lake Ristijärvi (7 km from Lehmilampi; Figure 2c), it was shown that the local forests burned in intervals of 220–260 years between c. 4350 BC and AD 1450 (Pitkänen et al., 2002). Similar fire regimes probably characterised most of the forests of the study region, including our study area. Thus the small-size fraction of microcharcoal in the record from Lehmilampi probably represents primarily the background microcharcoal input from regional fires.

We interpret the simultaneous occurrence of pollen indicators of human impact (following Gaillard, 2007), pollen cereals (Cerealia-type, *Hordeum*-type and/or *Secale*) and high values of large microcharcoal particles (>25–250 μm) (Figure 3a) as an indication of local slash-and-burn cultivation (Cornell, 2007). However, the occurrence of pollen from light-demanding plants alone – without a simultaneous occurrence of pollen from cereals – may just as well represent natural local disturbances (i.e. fire, wind, disease, etc.). The latter needs to be kept in mind when interpreting pollen data in terms of land use and human impact. Changes in palynological richness (estimated number of pollen taxa $E(Tn)$, see methods) are assumed to provide an estimate of changes in plant diversity at the biotope/vegetation level. $E(Tn)$ was shown to increase with disturbance intensity up to an intermediate level of disturbance (e.g. Berglund et al., 2008). Thus we assume that a high $E(Tn)$ is an additional indicator of disturbance in the record from Lehmilampi.

Below we refer to the archaeological chronology developed for the inland areas of eastern Finland. The major characteristics of the local pollen assemblage zones (LPAZs) are summarised in the electronic supplementary material (Table 1, available online). The pollen diagrams (Figure 3a, b) include the most abundant pollen types. Rare pollen findings are presented in the electronic supplementary material Table 2 (available online). We inferred four major periods of vegetation/forest disturbance (natural or human-induced); the three oldest periods are separated by two phases lacking signs of disturbances. The two last periods follow each other in time, but are different in character. Below we mainly discuss the inferred periods of vegetation/forest disturbance.



Analysis: F. Mazier

(Figure 3. Continued)

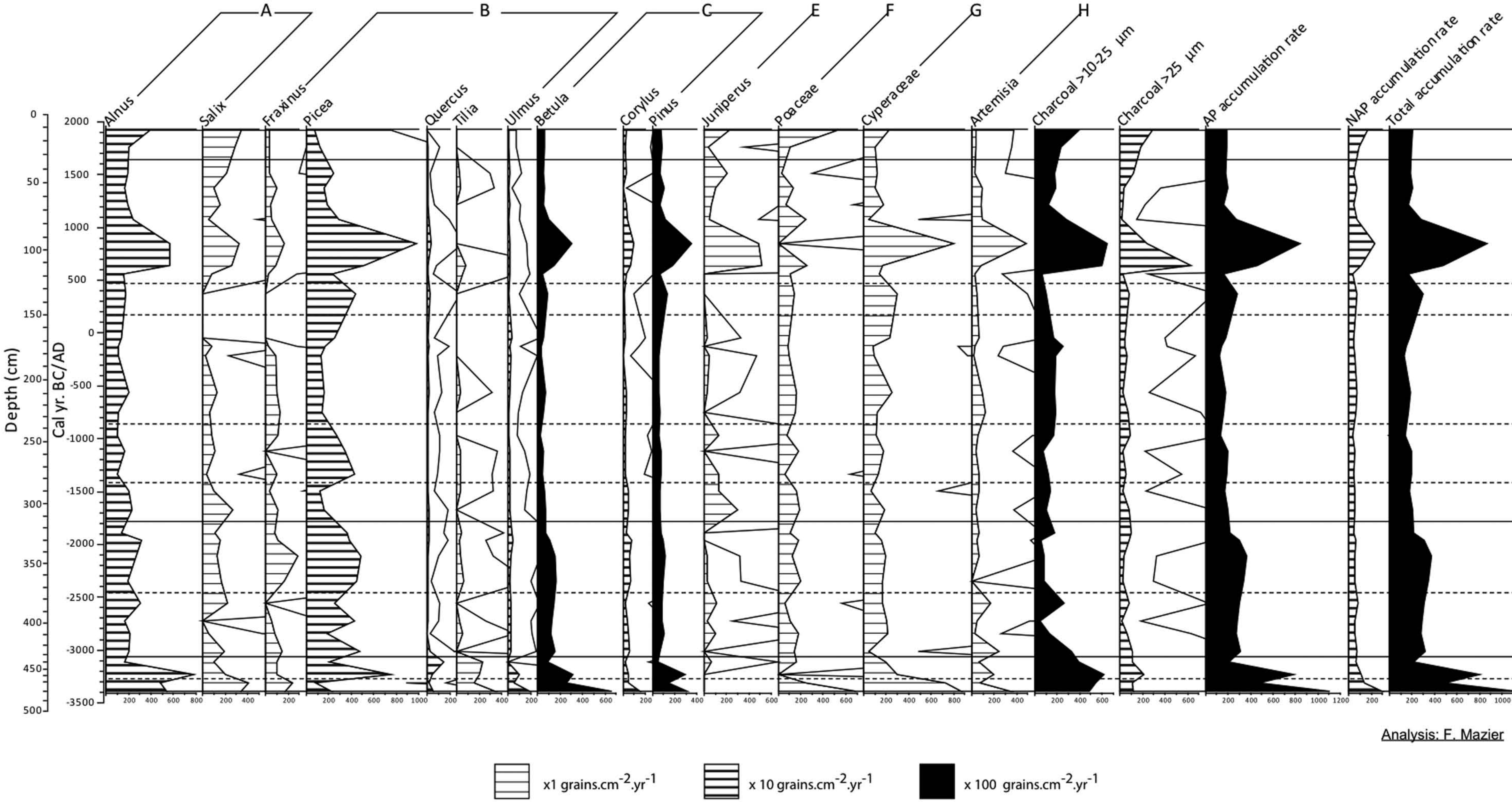


Figure 3. (a) Pollen and microcharcoal percentage diagram. Pollen grains of cereals were identified following Beug (2004), i.e. Cerealia-type is distinguished from wild grasses by the size of the grain, its pore diameter, and breadth and height of the annulus, which should be >37 µm, >2.7 µm, >2,7 µm, and >2.0 µm, respectively. Within the Cereal type group, *Hordeum*-type is distinguished by its round shape and exine sculpture (in phase contrast, isolated dark points, relatively large and regularly distributed), and *Secale* by its asymmetric shape. Some *Hordeum*-type pollen may belong to *Secale*, i.e. the *Secale* pollen morphological type may underestimate the amount of pollen from *Secale*. Moreover, the genera of wild grasses *Glyceria, Bromus, Agropyron* and *Elymus* have the same pollen morphology as *Hordeum*, i.e. they are included in the *Hordeum* type. The taxa groups A to I are according to Gaillard (2007) adapted for the purpose of this study. A: Trees and shrubs of damp soils; B: shade-tolerant trees and shrubs; C: light-demanding trees and shrubs; D: *Pteridium*; E: dry pastures and heaths; F: fresh meadows and pastures; G: Cyperaceae, *Sphagnum* (wet meadows); H: ruderal communities; I: cultivated land; J: *Dryopteris* type, *Huperzia selago*; L: lake vegetation. Pollen taxa, which are not shown in this diagram, are presented in Table 2 of the electronic supplementary material, available online. (b) Diagram of pollen accumulation rates for selected major pollen taxa. The taxa groups A–C and E–H are the same as in (a).

Table 1. Results of the sequential leaches, separated for samples with high erosion intensity (above the third quartile, Q3, of the original ash content data, n=493) and low erosion intensity (below the first quartile, Q1). The columns to the left show the sum of the three potentially mobile phases, in percent of the total accumulation of the element (Eq. 1). The relative difference between low and high erosion samples (Rel Diff) is given as the ratio of the <Q1/>Q3 values. Values above 1 mean that the total fraction of potentially mobile forms was higher in the low erosion rate material. As the values of the table are rounded, the decimals of the Rel Diff are in a few cases not corresponding to the <Q1/>Q3 of the tabled data. The three following columns state corresponding results for the three individual extractions.

	Sum of potentially mobile forms			Exchangeable forms and bound to carbonates			Forms in organic complexes			Forms associated with amorphous oxyhydroxides of Fe and Mn		
	> Q3	< Q1	Rel diff	> Q3	< Q1	Rel diff	> Q3	< Q1	Rel diff	> Q3	< Q1	Rel diff
Sr	2.6	7.0	2.7	1.3	4.1	3.3	0.67	1.35	2.0	0.79	1.56	2.0
Ca	7.8	16.7	2.1	3.4	10.5	3.1	0.7	2.6	3.7	3.6	3.6	1.0
Co	29	53	1.8	9.5	23.3	2.5	12	18	1.5	7.7	11.5	1.5
Zn	20	35	1.8	5.9	12.7	2.2	8.9	13.3	1.5	5	8.8	1.8
Ni	13	22	1.7	5.3	8.1	1.5	5.0	9.4	1.9	2.4	4.4	1.8
Ga	15	24	1.6	7.6	12.2	1.6	4.3	7.5	1.7	2.7	4.3	1.6
V	21	33	1.5	4.3	1.2	0.3	14	21	1.5	3.8	11.0	2.9
Y	24	37	1.5	9.7	11.5	1.2	11	19	1.7	3.6	6.2	1.7
Mg	3.1	4.7	1.5	0.44	1.57	3.6	1.7	2.5	1.5	0.93	0.64	0.7
Ba	16	24	1.5	3.5	4.8	1.4	2.1	3.4	1.6	10	16	1.5
Rb	1.7	2.3	1.4	0.27	0.41	1.5	0.85	1.16	1.4	0.58	0.77	1.3
La	26	34	1.3	6.6	7.2	1.1	14	17	1.3	5.8	9.3	1.6
Fe	32	42	1.3	5.2	4.9	0.9	22	25	1.1	8.8	12.6	1.4
K	2.8	3.6	1.3	0.56	0.83	1.5	1.9	2.4	1.2	0.32	0.41	1.3
Mn	73	92	1.3	59	71	1.2	8.9	14.5	1.6	5.1	6.8	1.3
Ce	33	42	1.3	8.4	9.0	1.1	19	22	1.2	6.5	10.7	1.6
U	38	44	1.1	20	22	1.1	13	18	1.5	5.6	3.1	0.6
Th	24	26	1.1	6.1	3.2	0.5	17	22	1.3	1.1	0.86	0.8
Cu	32	32	1.0	5.0	3.4	0.7	21	23	1.1	5.4	6.1	1.1
S	67	61	0.9	32	24	0.8	33	36	1.1	2.1	1.8	0.9
Pb	49	38	0.8	6.1	2.9	0.5	23	15	0.6	20	21	1.0
As	16	11	0.7	7.2	3.8	0.5	3.1	0.8	0.3	5.2	6.4	1.2

Neolithic time, c. 3000–2500 BC *(LPAZ 2a).* The first possible indications of human impact can be seen as early as the Neolithic time, between c. 3000 and 2500 BC (Figure 3a, b). Low but regular occurrences of *Juniperus*, Poaceae, *Artemisia*, Chenopodiaceae, *Plantago major, Rumex acetosa/acetosella, Filipendula* and *Ranunculus acris* are found, together with one finding of *Hordeum* type pollen and a few grains of *Anemone nemorosa* group, *Anthriscus sylvestris*, other Apiaceae, *Geum* and *Plantago major* (electronic supplementary material, Table 2, available online). All these taxa may have grown in forest openings created by human-induced disturbance (possibly cattle grazing) or natural disturbance. The *Hordeum* pollen-morphological type includes some genera of wild grasses (see methods above) and, therefore, is not an absolute proof of the cultivation of cereals. The current general opinion is that people were present in southern and eastern Finland since the Neolithic time, but that human influence on the landscape remained negligible until c. AD 1000 (the Viking Age) (Seppä et al., 2009). At Lake Ristijärvi (7 km from Lehmilampi), the earliest findings of human presence consist of low values of cereal pollen in sediment from the 13th century (Poutiainen et al., 1994). Nevertheless, a number of artefacts and settlements dated to the Neolithic were found not far from the lake catchment (Figure 2c) (Finland's National Board of Antiquities, 2012). To date, the earliest occurrence of cereal pollen grains in Eastern Finland is from the area of Lake Saimaa and was dated to c. 1400 BC (early Metal Period) (Vuorela, 1999; Vuorela and Kankainen, 1993).

LPAZ 2b (2500–1800 BC) is characterised by more sporadic occurrences of human-impact pollen indicators and no findings of cereal pollen. Therefore, it is interpreted as a period with little or no human/natural disturbance.

Early Metal Period, c. 1800–100 BC *(LPAZ 3a–3c).* The period of 1800–100 BC contains two episodes (LPAZ 3a 1800–1400 BC and LPAZ 3c 850–100 BC) with, in comparison to LPAZ 2 and 3d, relatively high values of large microcharcoal particles (> 25–250 µm), lower pollen values of *Picea*, slightly higher pollen values of Gramineae and Cyperaceae, and regular occurrences of *Juniperus, Artemisia*, Chenopodiaceae, *Hordeum*-type and *Pteridium. Sagina procumbens* group, *Geum* and *Cannabis sativa* occur with few grains (electronic supplementary material, Table 2, available online). There is also a slight rise in $E(Tn)$ values. A decrease in *Picea* has been explained earlier by its intolerance to fire (Grönlund, 1995) and *Juniperus* was proposed as one of the best indicators of grazing in Finland (Haegström, 1990). Furthermore, continuous findings of *Pteridium* have often been used as an indication of cultivation involving fire (Grönlund, 1995; Pitkänen, 1999). The more regular occurrence – and often larger amounts – of many of the human-impact indicators, as well as their higher diversity, the regular occurrence of *Hordeum* type and *Pteridium*, and the relatively high values of microcharcoals >25–250 µm during the two episodes (LPAZ 3a and 3c) all suggest that human interference is a probable explanation, possibly due to slash-and-burn cultivation and cattle grazing. The LPAZ 3b, 1400–850 BC, with higher values of *Picea*, lower values of Gramineae and $E(Tn)$, and the absence of *Pteridium*, may indicate a period with fewer fires and weaker human impact in terms of slash-and-burn, although most of the human-impact indicators mentioned above are still present, suggesting that cattle grazing still occurred in the study area.

Lake Heinälampi is the closest site with indications of human impact in the pollen record dated to c. 1300 BC (Figure 2b; Grönlund et al., 1992). Indications of human impact dating back to that time were also found in the area of Lake Saimaa (1400 BC), Lake Orijärvi (1600 BC; Alenius et al., 2008), and Lake Kirkkolampi (1950–1800 BC; Alenius and Laakso, 2006). The nearest archaeological evidence of settlement from that period in the study area is from Viitaniemi (Figure 2c).

LPAZ 3d (800 BC–AD 600) is characterised by sporadic occurrences of human-impact pollen indicators, no findings of cereal pollen, and low charcoal and $E(Tn)$ values. It is therefore interpreted as a period with little or no human disturbances.

Migration period (middle Iron Age) to late Middle Ages, AD 600–1500 (LPAZ 3e). Between c. AD 600 and 1500, the percentages of *Picea* decrease, *Artemisia* is represented during the entire period, and there are rare findings of Apiaceae, *Aster* type, *Epilobium angustifolium* type, *Galium* type, *Geum, Potentilla* type, *Ranunculus acris* group, *Silene vulgaris* group, and *Cannabis sativa* (electronic supplementary material Table 2, available online). The values of $E(Tn)$ also increase slightly, However, *Pteridium* is rare and there are no findings of Cerealia-type which, together with the generally low values of large microcharcoal particles, indicates that slash-and-burn was not practiced locally during most of the period. However, the high number of herb pollen taxa does indicate some disturbance and might reflect the occurrence of cattle grazing in the forest.

A large body of archaeological and palaeoecological records from southern and eastern Finland clearly demonstrate that farming started to develop at many sites during the Iron Age and increased in intensity during the Middle Ages (Alenius et al., 2008; Grönlund, 1995; Grönlund et al., 1992). Sporadic slash-and-burn agriculture of a similar age (AD 900) has been documented earlier in pollen records from northern Karelia (Grönlund, 1995; Grönlund and Asikainen, 1992; Grönlund et al., 1992). Cereal cultivation during that period was also found south of our study area (Figure 2b), at Lake Kirkkolampi (AD 300; Alenius and Laakso, 2006) and Lake Orijärvi (AD 600, Alenius et al., 2008). The reason why slash-and-burn was not practiced in the catchment of Lehmilampi at that time, but was practiced earlier (early Metal Period) and later (from c. AD 1500), is not known.

AD 1500–Modern times (LPAZ 4). A study by Pitkänen et al. (2002) indicates a drastic increase in forest fires about 500 years ago associated with stronger human impact in the area. The increase in percentage and accumulation rate of large microcharcoal particles c. AD 1500 in our study site, concurrent with an increase in *Salix, Juniperus* and *Rumex*, may be related to the same trend. From c. AD 1700, the pollen record indicates the cultivation of rye (*Secale*) and possibly barley (*Hordeum* type). Poaceae and *Rumex* increase from c. AD 1800 and reach their highest values in the profile, while *Picea* has very low values. Some indicators of human impact occur for the first time, including *Anthemis* type, Compositae SF Cichorioidae, and *Sinapis* type (electronic supplementary material Table 2, available online). Slash-and-burn was probably common locally from AD 1700. The continuous increase of $E(Tn)$ values over the last 300 years suggests that these land use changes resulted in a more fragmented and open forest vegetation with a higher biodiversity (Berglund et al., 2008). This interpretation is supported by the first mention of the town of Nurmes in written sources dating to AD 1556, the known existence of several farms in the area during the 17th century (Figure 2c), and the documented expansion of agriculture during the 18th century. During the 17th century, each farm had cultivated fields, and slash-and-burn was the dominant practice. Efforts were soon made to forbid slash-and-burn because of a wood shortage in many parts of southern and eastern Finland. Slash-and-burn decreased rapidly from mid AD 1800 onwards and was largely replaced by modern agriculture and sylviculture. The changes observed in the pollen record are also most probably related to the increase in the human population in North Karelia and the parallel increase in the amount of rye sown on arable land.

Controls on erosion intensity

Lake Lehmilampi was chosen for this study because the effects of within-lake processes on the sediment are assumed to have been small compared with the effects caused by changes in the catchment. Although there is a small fraction of organic matter in the clastic-organic varves that may originate primarily from authochtonous primary production (Haltia-Hovi et al., 2007), Lake Lehmilampi is a deep oligotrophic, clear-water lake where the material deposited in the deep basins is dominated by allochthonous mineral matter. The sediment is characterized by a low sediment accumulation rate and bioturbation from benthic animals is negligible. Moreover, the lake's large water volume in relation to its small catchment area implies a lake water retention time that allows for precipitation and accumulation in the lake sediment of suspended particles originating from the surroundings. Obviously, oligotrophic lakes may exhibit internal changes over time as a result of climate change. It is well known that, for example, changes in temperature or water stratification can affect the redox potential and leakage of elements from the sediment into the overlying water (Wetzel, 2001). However, no signs of such changes were detected in the sedimentary data and, therefore, we assume that the major processes affecting the geochemical properties of the lake sediments are terrestrial.

When discussing erosion intensity at Lake Lehmilampi we need to remember that changes are occurring in a relatively stable environment as indicated by the preservation of a varved sequence. The input rates cannot have reached extremes, otherwise the varves would not have been preserved. Also, the indicators of human disturbance in the sediment are assumed to originate from a relatively small area corresponding more or less to the size of the lake watershed catchment (1.5 km^2). The latter probably had a marginal location in relation to the major human activities around farms and villages, thus the disturbances in terms of open land and soil erosion were probably never very large in the lake catchment itself. Still, significant changes were registered in the sediment sequence.

The inferred erosion record at Lake Lehmilampi is shown in Figure 4. The highest erosion intensities coincide with periods characterised by human disturbance and local fire. The maximum erosion intensity is found during the most recent centuries, together with palynological evidence of cereal cultivation from AD 1700 onwards (possibly starting c. AD 1500). Erosion intensities that were almost as high are found c. 900–100 BC, along with indications of slash-and-burn. A third period of high erosion

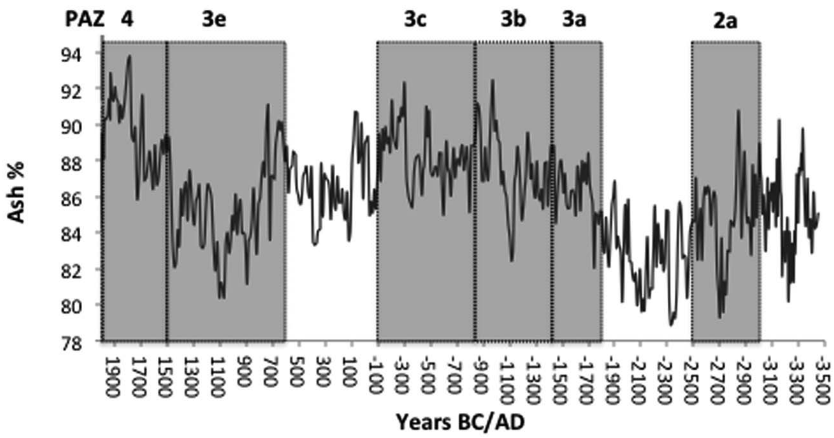


Figure 4. Inferred variations in erosion intensity, illustrated by ash content. Grey zones indicate the periods of natural or human-induced disturbances of the catchment and an increased openness of the landscape. For description of pollen assemblage zones (PAZs), please see the Land Use and Fire History Discussion.

intensity (AD 600–800) also includes signs of local fire, although the slash-and-burn practice is not confirmed by findings of cereal pollen in this case. During these three phases, human impact and the use of fire in the lake catchment may have caused significant destabilization of the surface soils and led to an increase in the outwash of detrital matter.

The 900–100 BC phase is the last part of a long period of human disturbances in the forest that started as early as c. 1800 BC. Erosion intensity was lower at the beginning of the period, possibly because of less intense human impact close to the lake. However, the erosion intensity started to increase by c. 2100 BC, before the first signs of human disturbances are seen. This initial increase may have been partly climate-induced. A significant climate shift towards colder and more humid conditions in Scandinavia between 2000 and 2500 BC, marking the end of the long-lasting Holocene Thermal Maximum (HTM), has been described in numerous studies (e.g. Dahl and Nesje, 1996; Digerfeldt, 1988; Hammarlund et al., 2003; Korhola, 1995; Korhola et al., 1996; Nesje et al., 2001; Seppä et al., 2005, 2009). This temperature decrease was also accompanied by more humid conditions, as indicated by the development of peatlands in Finland (e.g. Korhola, 1995; Korhola et al., 1996) and a rise in lake levels in southern Sweden (e.g. Digerfeldt, 1988; Eronen et al., 1999; Hammarlund et al., 2003; Seppä et al., 2005). Thus the increase in erosion rates observed from 2100 BC may be due to colder climate and increased precipitation. At the latitudes of Lehmilampi an increase in the duration of the winter season would have led to higher snow accumulation and thus increased surface runoff during snowmelt. An increased detrital input at the HTM termination has also been found in the varves of Lake Nautajärvi in central southern Finland, starting c. 2000 BC and followed by a continuous increase in mineral matter accumulation until c. AD 1 (Ojala and Alenius, 2005), which corresponds well to the trend seen at Lake Lehmilampi. An increased input to lake sediments has also been seen c. 2050 BC in Lake Igelsjön in southern Sweden (Jessen et al., 2005), and somewhat later, c. 1760 BC, in Lake Sarsjön in northern Sweden, which supports the theory of climate causing the increase in erosion intensity in Scandinavia at the end of the HTM.

The two periods with the most significant reduction in erosion intensity were found between 3000–2500 BC and AD 800–1500. There is no indication of local fire during these two periods, which suggests that slash-and-burn was not practiced in the surrounding area. Forest grazing might explain the occurrence of human-impact pollen indicators for the more recent of these two periods. The most likely factor affecting the two low-erosion periods should be sought on a regional level. First, because there are periods with higher erosion intensity in the record that lack human disturbances (c. 100 BC–AD 600). And in addition, low erosion intensities were also indicated in the record from Lake Nautajärvi during the same two periods (Ojala and Alenius, 2005). What the two periods have in common is that they were relatively warm and dry. The older of the two is found during the HTM, which has already been discussed above. The second one coincides with the 'Medieval Climate Anomaly' (MCA, AD 950–1250, Mann et al., 2009). This lower erosion intensity during the MCA was also recorded at Lake Korttajärvi and Lake Nautajärvi in south-central Finland (Figure 2b; Ojala and Alenius, 2005; Tiljander et al., 2003). As erosion intensity once again starts to increase around Lake Lehmilampi c. AD 1500, indicators of local fire suggest that slash-and-burn is practiced again. However, the role of human impact cannot be disentangled from the possible effect of the 'Little Ice Age' starting c. AD 1450 (Mann et al., 2009).

Climate change obviously played a significant role in the sediment accumulation and composition of Lake Lehmilampi during some periods of the Holocene. This was also shown by Haltia-Hovi et al. (2007), who found a strong positive correlation between varve thickness and solar activity. However, varve thickness is controlled mainly by the accumulation of organic matter, which has a high water content (Renberg et al., 1984). The accumulation of organic matter is mainly a function of autochtonous primary production and decomposition rates, and hence not suitable for tracking changes occurring in the catchment area. Haltia-Hovi et al. (2007) also present the results of mineral matter accumulation, which matches the ash content profile discussed in this paper. However, since their comparison with solar activity was not based on changes in the input of detrital mineral matter, their study and ours complement each other and show that lake sediments are controlled by both limnological processes (varve thickness) and terrestrial processes (mineral matter accumulation), where climate might be a strong forcing factor on processes both within the lake and in its catchment, but where the processes within the lake's catchment may also be strongly affected by human disturbances, natural forest fires, and other phenomena influencing both the erosion intensity and the physical and geochemical composition of the lake sediments.

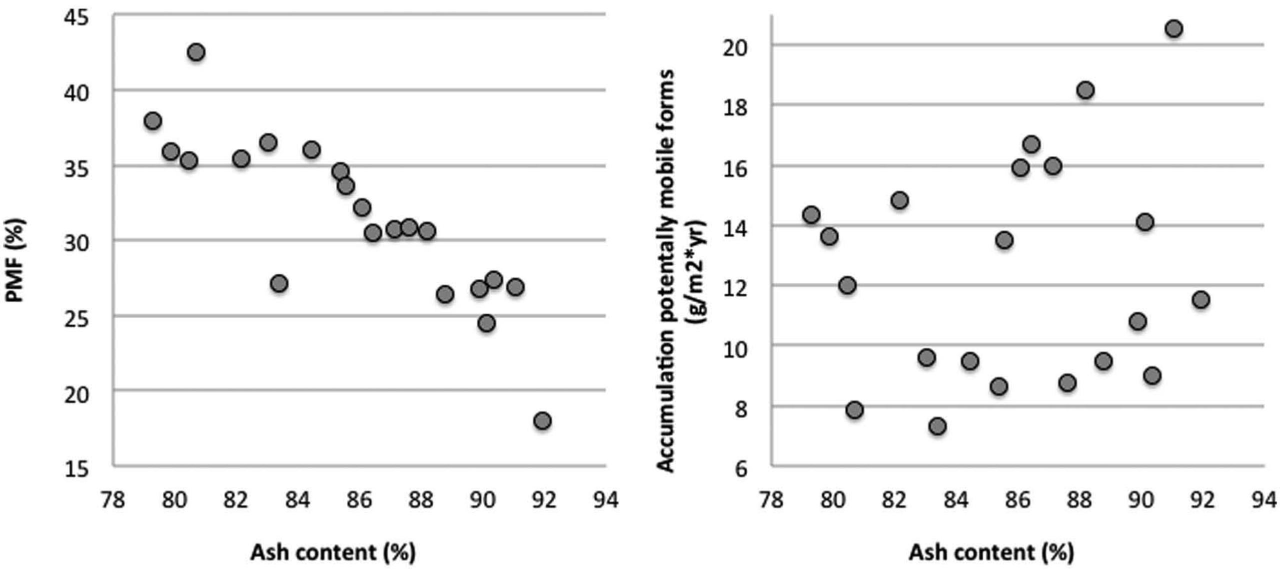


Figure 5. The total fraction of potentially mobile element forms (sum of the three sequential leaches for Al, As, Ba, Ca, Ce, Co, Cu, Fe, Ga, K, La, Mg, Mn, Ni, Pb, Rb, S, Sr, Th, U, V, Y and Zn) as a function of the rate of catchment erosion. Ash content values are used as a proxy for catchment erosion from the same samples, which were sequentially leached.

An increase in potentially mobile element forms during low erosion intensity

There is a clear negative correlation between the total *potentially mobile fraction* (PMF) of elements and the erosion intensity (r_s=−0.87; p<0.01; n=22) (Figure 5a). Each element's PMF is given in Table 1. The PMF varies from 10 to 90% depending on the element, which means that a substantial fraction of all elements was deposited in relatively unstable and easily leachable forms. The only elements with low values were Sr, Mg, K and Rb, all common in stable silicate minerals. All elements except S, Pb and As had a higher PMF in samples from periods with low erosion intensity. Of the 22 samples, the one with the highest erosion intensity contained a PMF of 18%, while the sample representing the lowest erosion intensity had a PMF of 38% (Figure 5a). The average annual accumulation of sediment was estimated to be 550 g/m^2 per yr for the sample with the highest estimate of erosion intensity, and 210 g/m^2 per yr (i.e. c. 40% of the 550 g) for the sample with the lowest estimate of erosion intensity (Augustsson et al., 2010). However, the higher PMF in the samples characterised by low erosion intensity compensates for the lower total sediment accumulation; thus the total accumulation of potentially mobile forms did not change much with changes in erosion intensity (Figure 5b). For example, the 18% PMF in the sample with the highest erosion intensity corresponds to 100 g/m^2 per yr of potentially mobile forms, and the corresponding value for the sample with the lowest erosion intensity is 80 g/m^2 per yr.

The decrease in PMF with erosion intensity could result from an increased input of coarser particles. As these particles should be more resistant to the leaching procedures applied, they would dilute more easily extractable forms. However, the lower PMF at high erosion intensities may also depend on altered conditions for leaching from the catchment. The impact of grain size effects and leaching are discussed below.

Effects of grain size changes on potentially mobile element forms. The lowest erosion intensities found during warm and dry periods might be explained by comparatively low surface water runoff. If this is the case, the average grain size of the eroded material might be lower during such periods, which has been indicated in the sediments of Lake Nautajärvi (Ojala and Francus, 2002). Since finer fractions are enriched in the species that were targeted in the sequential extraction, i.e. the potentially mobile forms, the high PMF values at low erosion intensity could result from a higher content of fine particles. However, no correlation was found between the ash content and the particle size. Figure 6 shows the results for the clay-size fraction (<2 µm), but the same lack of relationship appeared also when larger fractions were considered. The lack of systematic changes in the mechanical sorting of the fine fraction between periods of high and low erosion intensity was unexpected.

Effects of weathering and/or leaching. Is it then possible to explain the change in the PMF by a change in the chemical weathering regime and a subsequent change in leaching of soluble species from the catchment to the lake? It can be assumed that surface soils have more time to weather and podzolise during stable periods with low erosion intensity (Mackereth, 1966). During podzolisation elements are released from primary minerals by chemical weathering, and either lost by leaching or retained through precipitation of secondary minerals or adsorption onto solid particles (Lundström et al., 2000; Sauer et al., 2007). With an increase in leaching, there should be an increased transport of soluble elements with surface runoff and groundwater into lakes where precipitation might occur. In these forms the elements are more easily leached than from their original mineral structures. The elements that are retained in the soil after weathering are also more labile, which should be reflected in the lake sediment if such soils were eroded and transported to the lake.

An inverse relationship between chemical weathering and erosion intensity is not only suggested by the aspects of the podsolisation process described above. In the case of Lake Lehmilampi, it is also telling that the lowest erosion intensities were found during warm anomalies. Weathering intensity is sensitive to changes in climate, as temperature and humidity are critical for the rate of mineral dissolution (White et al., 1999), and for the decomposition

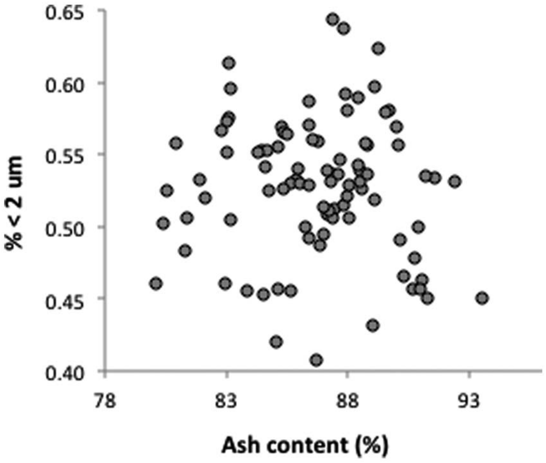


Figure 6. The percent of material in each sample that belonged to the clay sized fraction (<2 μm) plotted against the erosion rate, inferred from the ash content (*n*=91).

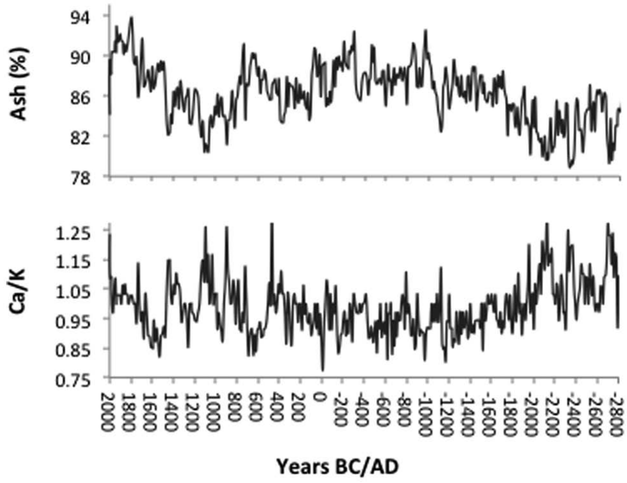


Figure 7. Variations in the Ca/K ratio in relation to variations in estimated erosion (inferred from ash content) of the catchment area.

of organic matter (Kirschbaum, 1995), a process which releases humic acids that further stimulate weathering. An increase in temperature may have a profound effect on the annual release of elements after weathering at sites where there is snow and ice for a significant part of the year. Past weathering intensities have been deduced from lake sediments using the ratios of Ca/K or Sr/Rb (Chen et al., 2005; Jin et al., 2001; Kauppila and Salonen, 1997; Solovieva and Jones, 2002). These ratios can provide robust evidence of weathering intensity since they are based on common elements, of which K and Rb are primarily associated with silicates and Ca and Sr are common in carbonates. As carbonates are more readily dissolved, the ratios should decrease in the parent material as weathering proceeds. In sediments, however, the ratios increase with an increase in weathering intensity. This is because solubilised and leached Ca and Sr ions easily form secondary phases that accumulate in the sediment. K and Rb, on the other hand, represent conservative elements. The fraction of these elements that is weathered remains dissolved and are thus less likely to end up in the sediment.

In Lehmilampi there is a clear negative correlation between erosion intensity and the ratios of both Ca/K (Figure 7) and Sr/Rb, which supports the idea of weathering being more pronounced during warmer periods with low erosion intensity.

Conclusions

(1) The pollen and charcoal analyses at Lake Lehmilampi (the first to be produced from the area) suggest that the first undisputable signs of human impact and practice of slash-and-burn cultivation date to 1800 BC (the early Metal Period) and lasted until 100 BC. There is archaeological evidence of settlement from that period c. 1.5 km north of the lake catchment. The first possible palynological signs of human impact (cattle grazing) occur during the Neolithic time, c. 3000–2550 BC, which is supported by archaeological records from the area. The catchment area was probably also used for grazing from c. AD 600 to 1500. Cereal cultivation is indicated once more from AD 1500 onwards and increased from AD 1700. There are three periods with low or no indication of natural or human disturbance: 3500–3000 BC, 2500–1800 BC, and 100 BC to AD 500.

(2) The highest erosion intensities were found during periods with local fire and human impact (slash-and-burn cultivation), i.e. 1800–100 BC (in particular 900–100 BC) and from AD 1500. During periods with little (cattle grazing) or no human disturbance in the catchment, the inferred erosion intensity is lower, suggesting that destabilisation of soils related to slash-and-burn practice is the most plausible explanation for the highest erosion intensities. However, the high erosion intensities from AD 1500 may just as well be related to the colder and more humid climate of the 'Little Ice Age' (AD 1450–1850). A climatic control is also suggested by the increase in erosion intensity at the termination of the HTM c. 2100 BC, which falls within a period with low or no indication of human impact.

(3) The lowest erosion intensities are clearly related to warm and dry climate conditions and the related effect on soil processes in the catchment during the HTM, 3500–2100 BC and the MCA (AD 950–1250). Before, during and after the MCA, i.e. the period AD 600–1500, the disturbances inferred from the pollen and charcoal record might reflect cattle grazing, which suggests that the changes in erosion intensity during that period are more likely related to climate change than land use.

(4) The records of erosion intensity, pollen and charcoal, combined with a general knowledge of the climate history of the region, clearly show that climate change and human impact both had an impact on erosion intensity during the 5500 years of environmental history covered by the sediment sequence studied here. The HTM, its end c. 2000 BC, and the MCA were major events that had a prominent effect on erosion intensity, while human impact may have been a more decisive factor between 3000 BC and AD 800 as well as in recent times, from AD 1700.

(5) Although the preserved varve sequence in Lehmilampi indicates a relatively stable environment in the lake's catchment, changes in erosion intensity were significant enough to affect the fraction of potentially mobile element phases; the latter clearly increases with decreasing erosion intensity. The increase in potentially mobile forms cannot be explained by an increased proportion of fine grained material, as no correlation was found between erosion intensity and the fraction of clay. Thus we assume that periods of low erosion inten-

sities were associated with a higher degree of chemical weathering and leaching.

(6) Detailed geochemical studies of annually laminated lake sediments, together with pollen and charcoal analyses, have a great potential for providing an in-depth understanding of how lake-catchment erosion and related geochemical properties in lake sediments may be affected by land use and climate change; sometimes they act together, and sometimes they play contrasting roles, depending on the time period. Annually laminated sediments are particularly useful in such studies as they make it possible to date significant changes with high accuracy and thus allow a precise correlation with information from other, independent sources such as archaeological data and proxy climate records.

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